Gamow-Teller Strengths in Proton-Rich Exotic Nuclei Deduced in the Combined Analysis of Mirror Transitions

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Isospin symmetry is expected for the $T_z = \pm 1 \rightarrow 0$ isobaric analogous transitions in isobars with mass number A, where T_z is the z component of isospin T. Assuming this symmetry, strengths of analogous Gamow-Teller (GT) transitions within $A = 50$ isobars were determined from a high energy-resolution $T_z = +1 \rightarrow 0$, ^{50}Cr(^{3}He, t)^{50}Mn study at 0° in combination with the decay Q value and lifetime from the $T_z = -1 \rightarrow 0$, ^{50}Fe $\rightarrow$ ^{50}Mn β decay. This method can be applied to other pf-shell nuclei and can be used to study GT strengths of astrophysical interest.

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In the core-collapse stage of type II supernovas, weak-interaction processes of pf-shell nuclei play important roles [1]. Therefore, studies of electron capture and β decay [2] caused by charged currents and neutrino-nucleus scattering [3] caused by neutral currents are of great astrophysical interest. The charged-current processes are dominated by Fermi and Gamow-Teller (GT) transitions, but the knowledge for the important GT transitions is very poor [2]. Direct information on the GT transition strength B(GT) can be derived from β-decay measurements. Pioneering studies were performed on several far-from-stability pf-shell nuclei (^{46}Cr, ^{50}Fe, ^{54}Ni, and ^{58}Zn) [4–7]. However, B(GT) values were derived for at most a few low-lying states with large ambiguities. Note that the study of the feeding to a higher excited state in β decay is difficult, because the phase-space factor (f factor) decreases with the excitation energy.

Charge-exchange (CE) reactions, such as (p, n), (n, p), (d, ^{2}He), or (^{3}He, t) reactions, can access GT transitions at higher excitations. In particular, it was shown that measurements at scattering angles around 0° and at intermediate beam energies above 100 MeV/nucleon were good probes of GT transitions. This is due to the fact that (a) GT states are dominant in the measured spectra, and (b) there is a simple proportionality between the GT cross sections at 0° and the B(GT) values [8]

$$\sigma^{\rm GT}(0°) \simeq K N_{\sigma\tau} |J_{\sigma\tau}(0)|^2 B({\rm GT}) \quad (1)$$

$$= \hat{\sigma}^{\rm GT}(0°) B({\rm GT}), \quad (2)$$

where K and $N_{\sigma\tau}$ are kinematic and distortion factors, respectively, $J_{\sigma\tau}(0)$ is the volume integral of the effective interaction $V_{\sigma\tau}$ at momentum transfer $q = 0$, and $\hat{\sigma}^{\rm GT}(0°)$ is the GT unit cross section at 0° for a specific mass A system. Therefore, the study of B(GT) values can reliably be extended up to high excitations if a "standard B(GT) value" from β decay is available.

Studies of GT strengths in pf-shell nuclei using (p, n) and (n, p) reactions at intermediate energies started in the 1980s. They provided rich information on the overall GT strength distributions [9], but individual transitions were only poorly studied due to their limited energy resolutions of ≈300 keV and ≈1 MeV, respectively. Therefore, there was no direct way to calibrate the unit cross section $\hat{\sigma}^{\rm GT}(0°)$ by using β-decay standard B(GT) values [8]. In addition, the standard B(GT) values, as mentioned, are poorly known for pf-shell nuclei.

A development in precise beam matching techniques [10] realized an energy resolution of ≈30 keV in intermediate energy (^{3}He, t) reactions at 0° [11]. With this one-order of magnitude better resolution, we can now study GT and Fermi states that were unresolved in the pioneering (p, n) reactions. In addition, the validity of the proportionality [Eq. (2)] was examined by comparing the GT transition strengths in the (^{3}He, t) spectra to the B(GT) values from mirror β decays. Good proportionality was demonstrated for "$L = 0$" transitions with B(GT) ≥ 0.04 in studies of the $A = 26$ and 27 nuclear systems [12,13]. By exploiting these splendid properties, we present here a unique analysis to determine absolute B(GT) values by combining the precise strength distribution from the (^{3}He, t) reaction with the decay Q value and lifetime from the mirror β decay.

Under the assumption that isospin T is a good quantum number, an analogous structure is expected for nuclei with the same mass A but with different T_z (isobars), where $T_z[= (N - Z)/2]$ is the z component of isospin T (see, e.g., Ref. [14]). The corresponding states in isobars are called isobaric analog states (or simply analog states) and are expected to have the same nuclear structure. Various transitions connecting corresponding analog states are also analogous and have corresponding strengths. In the "$T = 1$ triplet," GT and also Fermi transitions from the $J^\pi = 0^+$ ground states (g.s.) of the $T_z = \pm 1$ even-even nuclei to 1^+ states (GT states) and the 0^+ state in the $T_z = 0$ odd-odd nucleus between them are analogous, respectively (see Fig. 1). In the pf-shell region, $T_z = +1 \rightarrow 0$ transitions can be studied via $(^3\mathrm{He}, t)$ reactions on five stable $T_z = +1$ target nuclei, and analogous $T_z = -1 \rightarrow 0$ transitions can be studied via β decays. Assuming that the analogous GT transitions have the same $B(\mathrm{GT})$ values, the $B(\mathrm{GT})$ values from β decays [4–7] can, in principle, be used as standard $B(\mathrm{GT})$ values. Then the study of $B(\mathrm{GT})$ distributions can be extended by the $(^3\mathrm{He}, t)$ reactions to higher excitation energies, overcoming the limits imposed by the Q values in β decays. However, due to large uncertainties of β-decay $B(\mathrm{GT})$ values, this idea was not practical.

In a β decay, the partial half-life t multiplied by the f factor is related to the $B(\mathrm{GT})$ and the reduced Fermi transition strength $B(\mathrm{F})$,

$$ft = K/[B(\mathrm{F})(1 - \delta_c) + \lambda^2 B(\mathrm{GT})], \qquad (3)$$

where $K = 6144.4 \pm 1.6$ [15], $\lambda = g_A/g_V = -1.266 \pm 0.004$ [16], and δ_c is the Coulomb correction factor. The Fermi strength is concentrated in the transition to the isobaric analog state (IAS) of the g.s. of the mother nucleus and has the value $|N - Z|$. Uncertainties in $B(\mathrm{GT})$ values originate from uncertainties in the decay Q value, the total half-life $T_{1/2}$, and the branching ratios (feeding ratios) determining t. The accurate determination of the feeding ratios to higher excited states is more difficult due to smaller f factors. On the other hand, in the studies of analogous GT transitions using $(^3\mathrm{He}, t)$ reactions, relative

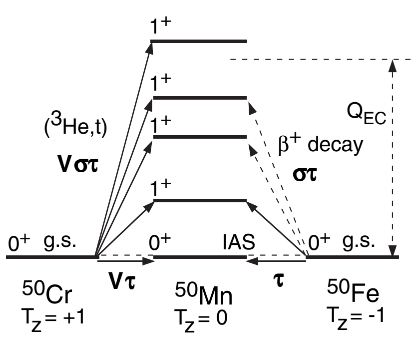

FIG. 1. Schematic view of the isospin symmetry transitions from the $T_z = \pm 1$ nuclei to the $T_z = 0$ nucleus in the $A = 50$ isobar system. The Coulomb displacement energies are removed. The β decays to higher excited states are more suppressed by smaller phase-space factors f.

transition strengths to these higher excited states can be obtained accurately from the $\sigma^{\mathrm{GT}}(0°)$ values. It should be noted that the β-decay feeding ratios can be deduced using these values and f factors that are calculated from the decay Q value. Absolute $B(\mathrm{GT})$ values can then be deduced by further combining the total half-life $T_{1/2}$ of the β decay. Among the $T = 1$ triplets in the pf-shell region, these values are best known for the $A = 50$ system, i.e., for the $^{50}\mathrm{Fe} \rightarrow {}^{50}\mathrm{Mn}$ β decay [$T_{1/2} = 0.155(11)$ s and $Q_{\mathrm{EC}} = 8.15(6)$ MeV]. However, so far the feeding was detected only to the first GT state at the excitation energy $E_x = 0.651$ MeV [5]. Therefore, a $B(\mathrm{GT})$ value of 0.60(16) was deduced under the extreme assumption that there was no feeding to higher excited states [5].

Let us make this idea of $B(\mathrm{GT})$ determination realistic. The inverse of $T_{1/2}$ is the sum of the inverse of the partial half-life t_{F} of the Fermi transition to the IAS and those of t_i's of GT transitions to the ith GT states

$$(1/T_{1/2}) = (1/t_{\mathrm{F}}) + \sum_{i=\mathrm{GT}} (1/t_i). \qquad (4)$$

Applying Eq. (3), t_{F} and also t_i's can be eliminated,

$$\frac{1}{T_{1/2}} = \frac{1}{K}\left[B(\mathrm{F})(1 - \delta_c)f_{\mathrm{F}} + \sum_{i=\mathrm{GT}} \lambda^2 B_i(\mathrm{GT}) f_i\right], \qquad (5)$$

where f_{F} and f_i are the f factors of the β decay to the IAS and to the ith GT state, respectively, and $B_i(\mathrm{GT})$ is the $B(\mathrm{GT})$ value of the transition to the ith GT state. In order to relate the strengths of GT and Fermi transitions in a CE reaction, we introduce the ratio R^2 of unit GT and Fermi cross sections at 0°

$$R^2 = \frac{\hat{\sigma}^{\mathrm{GT}}}{\hat{\sigma}^{\mathrm{F}}} = \frac{\sigma_i^{\mathrm{GT}}}{B_i(\mathrm{GT})} \Big/ \frac{\sigma^{\mathrm{F}}}{B(\mathrm{F})(1 - \delta_c)}. \qquad (6)$$

Owing to the isospin symmetry, this ratio R^2 is expected to be the same for the $T_z = \pm 1 \rightarrow 0$ transitions. Eliminating $B_i(\mathrm{GT})$ by using R^2, we get

$$\frac{1}{T_{1/2}} = \frac{B(\mathrm{F})(1 - \delta_c)}{K\sigma^{\mathrm{F}}}\left[\sigma^{\mathrm{F}} f_{\mathrm{F}} + \frac{\lambda^2}{R^2} \sum_{i=\mathrm{GT}} \sigma_i^{\mathrm{GT}} f_i\right], \qquad (7)$$

where $B(\mathrm{F}) = 2$ and $\delta_c = 0.0051(4)$ [15] can be used for the β decay of $^{50}\mathrm{Fe}$.

Accurate (relative) cross sections of the IAS and excited GT states should be measured in the $T_z = +1 \rightarrow 0$, $^{50}\mathrm{Cr}(^3\mathrm{He}, t)^{50}\mathrm{Mn}$ reaction. This experiment was performed at the high energy-resolution facility of the Research Center for Nuclear Physics (RCNP), consisting of the beam line called "WS course" [17] and the Grand Raiden spectrometer [18] using a 140 MeV/nucleon $^3\mathrm{He}$ beam from the $K = 400$ Ring Cyclotron [19]. A self-supporting foil of $^{50}\mathrm{Cr}$ with an areal density of 0.75 mg/cm^2 and an isotopic enrichment of 95.9% was used. The outgoing tritons were momentum analyzed within the full acceptance of the spectrometer placed at

0° and detected with a focal-plane detector system allowing for particle identification and track reconstruction in horizontal and vertical directions [20]. A good resolution of scattering angle $\Delta\Theta \approx 5$ mrad [full width at half-maximum (FWHM)] was achieved by applying the *angular dispersion matching* technique [10] and the "overfocus mode" of the spectrometer [21]. The acceptance of the spectrometer was subdivided in scattering-angle regions in the analysis using the track information.

An energy resolution of $\Delta E = 29$ keV (FWHM), which is better by a factor of 5 than the energy spread of the beam, was realized by applying both the *dispersion matching* and the *focus matching* techniques [10,22]. The "0° spectrum" for the events with $\Theta \leq 0.5°$ is shown in Fig. 2(a) up to $E_x = 6$ MeV. Well separated ^{50}Mn states were observed owing to the high energy resolution. Weak states of ^{52}Mn originating from the 3.8% ^{52}Cr isotope in the target were identified by consulting the spectrum of an enriched ^{52}Cr target.

The g.s. of ^{50}Mn is the $J^\pi = 0^+$ IAS of the target nucleus ^{50}Cr [23]. Since the GT state was known only at 0.651 MeV [5,23–25], E_x values of higher excited states were determined with the help of kinematic calculations using well-known E_x values of ^{26}Al, ^{24}Al, and ^{16}F states in the spectrum from a polyvinylalcohol-supported $^{\mathrm{nat}}$MgCO$_3$ thin foil target [26] as references. All E_x values of ^{50}Mn states listed in Table I were determined by interpolation. Estimated errors are less than 4 keV (for details, see Refs. [27,28]). In order to distinguish GT states with "$L = 0$" nature, intensities of observed states were compared in the spectra for two angle cuts $\Theta = 0°$–$0.5°$ and $1.5°$–$2.0°$. All prominent states showed 0° peaked angular distributions, suggesting an $L = 0$ nature. Since the Fermi strength is concentrated in the transition to the IAS, it is very probable that these $L = 0$ states are all GT states. Intensities of several weakly excited states increased at larger scattering angles, suggesting an "$L \geq 1$" nature (see Table I).

The unit GT cross section in Eq. (2) gradually decreases as a function of excitation energy [8]. A distorted wave Born approximation calculation showed that the correction was small and about 4% at 4.6 MeV (for details, see Refs. [27,28]). In order to obtain an accurate Fermi cross section (or intensity) of the transition to the g.s. IAS of ^{50}Mn, contributions from other manganese isotopes to the IAS peak were subtracted. The Fermi intensity inherent to the ^{50}Mn was estimated to be 92.0% of the observed IAS peak using the known abundances of chromium isotopes in the target assuming that each Fermi transition carries the full strength of $B(\mathrm{F}) = N - Z$ and the same unit Fermi cross section.

Equation (7) shows that the inverse of $T_{1/2}$ is proportional to the sum of intensities of the observed Fermi and GT states weighted by f factors, where a further correction factor λ^2/R^2 is needed for the GT intensities to compensate for the differences of coupling constants in the Fermi and GT β decays and unit Fermi and GT cross sections in the (^{3}He, t) reaction. The f factors were calculated following Ref. [29]. Values normalized to unity at $E_x = 0$ are shown in Fig. 2(b). By assuming good isospin symmetry, the energy spectrum of GT transitions in the ^{50}Fe β decay

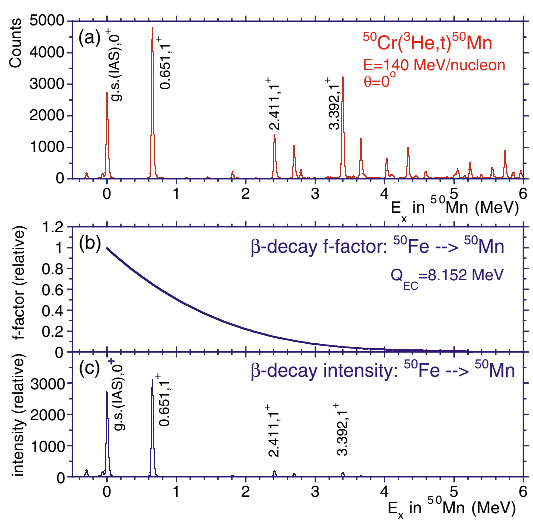

FIG. 2 (color online). (a) The ^{50}Cr(^{3}He, t)^{50}Mn spectrum for events with scattering angles $\Theta \leq 0.5°$. Major $L = 0$ states are indicated by their excitation energies in MeV. (b) The f factor for the ^{50}Fe β decay, normalized to unity at $E_x = 0$ MeV. (c) The estimated ^{50}Fe β-decay energy spectrum that is obtained by multiplying the f factor to the ^{50}Cr(^{3}He, t) spectrum. Note that the IAS is stronger by a factor of R^2/λ^2 in the real β-decay measurement (see text).

TABLE I. States observed in the ^{50}Cr(^{3}He, t)^{50}Mn reaction below $E_x = 4.6$ MeV. For the $L = 0$ states, B(GT) values are given.

Evaluated values[a]		(^{3}He, t)[b]		
E_x (MeV)	J^π	E_x (MeV)	L	B(GT)
0.0	$0^{+\,\mathrm{c}}$	0.0	0	
0.651	1^+	0.652	0	0.50(13)
0.800	2^+	0.800	≥1	
1.143	3^+	1.147	≥1	
1.802	3	1.805	≥1	
		2.411	0	0.15(4)
		2.694	0	0.11(3)
		2.790	0	0.03(1)
		3.177	≥1	
		3.392	0	0.35(9)
		3.654	0	0.14(4)
		4.028	0	0.07(2)
		4.333	0	0.11(3)
		4.584	0	0.03(1)

[a]From Refs. [23,24].
[b]Present work.
[c]The IAS with $T = 1$.

can be estimated by multiplying the ^{50}Cr(^{3}He, t) spectrum with the f factor [Fig. 2(c)].

This predicted β-decay spectrum shows that no significant contribution is expected from GT states higher than 4.6 MeV to the second term of the right-hand side of Eq. (7). Furthermore, it suggests that more than an order of magnitude better sensitivity was needed to detect the transitions to the second and higher excited GT states in the measurement of the ^{50}Fe β decay. The estimated feedings to these excited GT states amount in total to about 20% of the feeding to the first 0.651 MeV GT state, although each of them is small. By solving Eq. (7), we get a value $R^2 = 7.5 \pm 2.0$. The error mainly comes from the uncertainty in the $T_{1/2}$ value in the β-decay measurement and also from the f factor. The "absolute" B(GT) values calculated using Eq. (6) are listed in column 5 of Table I. It should be noted that the excitation energy of 4.6 MeV analyzed presently is far above the reach of the ^{50}Fe β-decay study. Owing to the newly estimated feedings to higher excited GT states, the B(GT) value of the first GT state decreased by about 20% from the β-decay value of 0.60(16) to 0.50(13). Besides these statistical errors, there may be systematic errors due to wrong L assignment. We, however, consider this rather unlikely.

In conclusion, we performed a ^{50}Cr(^{3}He, t)^{50}Mn experiment at an intermediate beam energy of 140 MeV/nucleon to study $T_z = +1 \rightarrow 0$ GT transitions. With a high energy-resolution of 29 keV, discrete GT states were identified. Taking advantage of the good proportionality between the GT cross sections at 0° and the B(GT) values, the unknown "energy spectrum" of the $T_z = -1 \rightarrow 0$ ^{50}Fe β decay was estimated by multiplying the f factor calculated from the Q value of the decay. By further combining the half-life $T_{1/2}$, absolute values of GT transition strengths B(GT) were derived. Note that no feeding information, which is difficult to measure in a β decay, is used.

This "merged analysis" of determining absolute GT strengths by combining the complementary information from isospin mirror transitions can be extended to other $T = 1$ systems and also to $T = 2$ and even higher T systems, thus allowing one to deduce the GT strength distributions in proton-rich exotic nuclei. Note that the development of new methods, such as using various ion traps, is in progress for the accurate measurement of the $T_{1/2}$ and the Q values of these far-from-stability nuclei. The better knowledge on them will make this merged analysis even more fruitful as the means to determine the GT strengths, which are needed to deduce the astrophysical transition rates under extreme conditions.

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